Developing Methods to Predict N_2O Emissions in Crop Production Systems

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Background / Introduction

The atmospheric concentration of nitrous oxide (N_2O) has increased from approximately 0.28 ppmv in pre-industrial times to a current level of about 0.31 ppmv. This increase is cause for considerable concern, since N_2O is a highly potent greenhouse gas, accounting for 6 to 8% of the present greenhouse forcing rate ascribed to anthropogenic sources. Over a 100 year period it absorbs infrared radiation about 310 times more effectively than CO_2, on a molar basis. N_2O also enters into catalytic reactions that influence the stratospheric ozone (O_3). Increased amounts of N_2O reaching the stratosphere will reduce the concentration of O_3, which shields the planet from biologically damaging ultra-violet radiation.

Globally, anthropogenic sources represent about 24% of total N_2O emissions, with nearly all (92%) of the anthropogenic emissions being attributed to agricultural activities. In Canada, agriculture's share of total anthropogenic N_2O emissions is estimated to be about 59%. Canadian agriculture's relative contribution is less because land use patterns are relatively stable, and organic matter levels are at or approaching equilibrium in agricultural soils.

Recent political events underscore the growing concern regarding the increase of N_2O and other greenhouse gases on our global environment. Canada, a signatory of the Kyoto Protocol, has committed itself to reducing national greenhouse gas emissions to 6% less than 1990 levels by the period 2008-2012. In order to meet this objective we must first accurately estimate those emissions, in order to develop effective strategies to reduce emissions within a discrete period of time. Agroecosystems are managed systems, therefore there is opportunity to select for management strategies that would minimize greenhouse gas emissions. Indeed, since agricultural soils have lost about 25% of their organic carbon, it is hoped that innovative management strategies could cause

an increase soil organic matter. Agricultural soils would then serve as a net sink of CO_2-C by removing it from the atmosphere and storing it in soil organic matter reserves. A watchful eye must be cast on the effect that these strategies may have on N_2O emissions. Considering its high global warming potential, even small concurrent increases in N_2O emissions would quickly offset CO_2 –C removals. In general, management strategies that increase N-use efficiency are most likely to decrease N_2O emissions. However, the conditions that govern N_2O production and emission are complex, and many interactions must be considered.

Accurate estimates of annual N_2O emissions at the field, regional and country wide scale are required to: i) establish baseline values, ii) compare current management strategies and identify best management practices, and iii) evaluate and monitor the impact of management changes. However, the spatial and temporal variability of N_2O emissions are very large, making both quantification and prediction difficult. Scaling-up techniques and simulation models that are dynamic enough to account for the spatial and temporal variability are urgently needed. Appropriate models would improve the reliability of temporal and spatial integrations, but also test our current knowledge so that gaps can be identified and addressed. They are also needed as predictive tools for investigating and assessing the influence of changing management and/or climate scenarios on N_2O emissions.

Difficulties in Quantifying N_2O Emissions

The key difficulty to quantifying N_2O emissions is the extreme temporal and spatial variability of the emission. The seasonal distribution of N_2O emissions has been relatively well characterized. The timing of N_2O emission events is determined by the influence of precipitation, temperature, and management practices such as fertilizer or manure application and tillage. When these elements intersect to create favorable soil-water contents, N and C availability, and temperature, substantial N_2O emissions can be anticipated. On the other hand, our ability to predict the actual magnitudes of N_2O flux from a particular point at a particular time is far from satisfactory, particularly during the spring burst, upon snow melt.

N_2O emission rates may vary by an order of magnitude or more over distances of just meters. Large scale measurement techniques (tower, eddy correlation) can accommodate this variability by integrating fluxes over large surface areas, however logistics preclude their use for process level studies and other studies that require replicate measurements coincident in space or time. Chamber techniques or "point measurements" are still the method of choice for most N_2O flux studies The CV between replicate point measurements typically range between 60 to 150%, with values as high as 300% reported. This is problematic for statistical treatment of the data, and introduces a high degree of uncertainty into extrapolations over time or space.

This large spatial variability is a result of the multitude and complexity of factors that influence N_2O emissions. Firstly, N_2O can be produced by at least two separate processes, nitrification and denitrification, which can occur simultaneously. The rate of each process responds to different controls, or in some instances, the same controls but opposing responses. Secondly, the amount of N_2O produced is not only a reflection of the rate of these processes, but also of the yield of N_2O per unit N nitrified and denitrified. The ratios of N_2O to NH_4^+ nitrified or NO_3^- denitrified, are governed by another related but distinct set of controls. Nitrification and denitrification are carried out by microorganisms. These organisms are responding to conditions at a cellular or microscopic scale, conditions that may vary over scales of micrometers or millimeters. Measurements that are meaningful for N_2O flux studies, however, are taken at scales of centimeters or meters, scales that are one or more orders of magnitude greater.

Lastly, N_2O produced within the soil profile is not instantaneously emitted from the soil surface. There can be a considerable time lag between production and emission. In addition, production rates are not linearly related to emission rates since the N_2O produced can be further reduced to N_2 during transport to the soil surface. Soil conditions observed at the time of emission may not necessarily reflect the conditions experienced at the time of production.

Methods of estimating N_2O emissions on a national level

Interpolation from experimental data

Not enough experimental data sets exist to sufficiently characterize N_2O emissions for a country with as much size and diversity as Canada. Often there are no more than a few experimental sites within a soil region. The data from experimental sites is most useful for understanding model processes and developing algorithms.

IPCC

The IPCC has developed a methodology for calculating national emissions of N_2O from agriculture (IPCC, 1996a,b). Three sources of N_2O emissions are identified: i) direct emissions from agricultural soils, ii) emissions from animal production, and iii) N_2O emissions indirectly induced by agricultural activities. Direct emissions from agricultural soils are estimated by a simple linear extrapolation between anthropogenic N "inputs" and N_2O emissions. Anthropogenic N inputs include synthetic fertilizer, N from animal excreta applied as fertilizer, N from biological N-fixation, and N derived from enhanced organic matter mineralization resulting from agricultural activities. Emissions from animal production include direct emissions from the animals, emissions during storage, treatment and handling of the animal excreta, and N_2O arising from the deposition of urine and dung by grazing animals. Indirect emissions refer to increased N_2O emissions that result from N that is transported from agricultural systems into other ecosystems. This includes N transported via surface runoff and leaching, NH_3 and NOx volatilization and deposition, and human consumption and subsequent disposal of N containing sewage sludge.

Total N_2O emissions arising directly from agriculture is calculated using the following linear equation:

$$\text{Total } N_2O \text{ DIRECT} = [(FSN + FAW + FBN + FCR) * EF1] + FOS * EF2$$

where:

N_2O DIRECT = direct N_2O emissions from agricultural soil (kg N y^{-1})

FSN = N added as synthetic fertilizers (kg N y^{-1})

FCR = N in crop residues returned to soils (kg N y^{-1})

FAW = animal waste N used as fertilizer (kg N y^{-1})

FBN = N fixed by N-fixing crops (kg N y^{-1})

FOS = area of cultivated organic soils

EF1 = emissions factor for direct soil emissions (kg N_2O-N [kg N input]$^{-1}$)

EF2 = emission factor for organic soil mineralization due to cultivation

The methodology was designed so that all necessary inputs would be available from FAO databases. FSN can be calculated from the total fertilizer N used within the country, FAW from the number and type of animals, FNB and FCR are calculated from respective crop production statistics. N lost through volatilization processes is to be first removed from the value used for FSN. Similarly, the value used for FAW is also net of volatilization losses, any fraction used as fuel, and the fraction attributed to free ranging animals (not applied to cropland as fertilizer). Volatilization losses are assumed to be 10% for synthetic fertilizers and 20% for animal wastes. FBN only considers pulses and soybeans, and does not reflect N_2O production from legumes in mixed pastures or forage crops. Total N input for FBN is calculated by assuming a single fixed N content for total crop biomass, which is assumed to be twice the edible portion, i.e. that portion reported in production data. FCR is calculated from the total crop biomass, estimated as twice the grain yield minus the amount of residue removed from the field, and assuming one N content for all non-N-fixing crops and one N content for all N-fixing crops.

The approach does not reflect different crops, soils, or climates, all of which are thought to influence N_2O production, but considers all agricultural systems to be the same. These factors have not been considered because of the limited data available to provide emission factors (OECD/IPCC, 1997). A range of emission factors are provided however, and some adjustment for specific conditions within a country can be made through careful selection of these factors.

The contribution of N_2O arising from animal production is calculated as:

$N_2OANIMALS = N_2ODIRGAS + N_2OAWMS$

where:

$N_2OANIMALS$ = N_2O emissions from animal production and pastures (kg N y^{-1})

$N_2ODIRGAS$ = direct N_2O emissions from animals (kg N y^{-1})

N_2OAWMS = N_2O emissions from Animal Waste Management Systems (kg N y^{-1})

The contribution of Animal Waste Management Systems (N_2OAWMS) is calculated by assigning specific emission factors, expressed as a % of total N excreted, to specific handling systems. Examples of Animal Waste Management Systems include pasture range, liquid systems, anaerobic lagoons. Total N excreted can be calculated from default values provided and the number of each type of animal (dairy cattle, sheep, poultry etc.).

Indirect N_2O emissions are calculated as:

$N_2OINDIRECT = N_2O(G) + N_2O(L) + N_2O(S)$

where:

$N_2OINDIRECT = N_2O(G) + N_2O(L) + N_2O(S)$

$N_2O(G)$ = N_2O produced from atmospheric deposition (kg N y^{-1})

$N_2O(L)$ = N_2O produced from N leaching and runoff (kg N y^{-1})

$N_2O(S)$ = N_2O produced from human sewage (kg N y^{-1})

$N_2O(G)$ is arrived at by multiplying the total amount of N being deposited from the atmosphere by an emission factor. The total N being deposited is assumed to be that fraction of synthetic fertilizer and manure N applied to agroecosystems that volatilizes. Similarly, total N leached is calculated as a fraction of the total N applied in synthetic fertilizers and manure. This total is in turn multiplied by an emission factor to arrive at $N_2O(L)$. Multiplying the annual per capita protein consumption by the number of people in the country provides an estimate of total protein consumed. Multiplying this value by an appropriate factor provides the total protein in sewage sludge, which is then multiplied by an emissions factor to estimate $N_2O(S)$.

Models

The most important processes for N_2O production in soils are denitrification and nitrification (Li et al. 1994). These processes are influenced by environmental factors such as temperature, rainfall/snowmelt, freezing and thawing. Agricultural management practices such as manure/fertilizer application, incorporation of crops or crop residue, and tillage also influence N_2O production and emission. Several simulation models which describe nitrogen dynamics in soils have been developed. Some of these models (Van Veen and Frissel 1979; Molina et al. 1983; Clay et al. 1985; Johnsson et al. 1991) predict total losses of N from soils in the field but model only denitrification without separating N_2O and N_2, while others (McConnaughey and Bouldin 1985; Leffelaar and Wessel 1988) model the separate processes of denitrification but do not use field scale variables. The model by Grant (1996) includes all major processes but requires detailed data which may not always be available at the field scale. It should also be noted that the code has not yet been transferred to personal computers.

The DNDC (DeNtrification DeComposition) model by Li et al. (1992a,b) includes the processes of denitrification and nitrification and provides daily or seasonal N_2O evolution from agricultural soils, using readily available input data. The model consists of four interacting submodels. A thermal-hydraulic submodel calculates soil temperature and moisture profiles and soil water fluxes from daily air temperature and precipitation data and soil texture. This information is then fed into other three submodels. A decomposition submodel calculates daily carbon decomposition, nitrification, ammonia volatilization and soil microbial respiration. The decomposition submodel calculates carbon and inorganic nitrogen pools and dissolved organic carbon availability. Available inorganic N is the key process linking this submodel with the Plant Growth submodel. The Plant Growth submodel calculates daily root respiration, as well as water and N utilization, based on N availability provided by the decomposition submodel, soil environmental conditions (moisture and temperature) provided by the Soil Climate submodel and external inputs regarding, tillage and cropping practices. The denitrification sub-model calculates hourly N_2O and N_2 production during periods when water-filled pore space is greater than 40%. Denitrification is modified by the N and DOC availability inputs from the decomposition submodel, and the soil environmental conditions provided by the Soil Climate submodel.

Inputs are required in three different areas. Firstly, climate files consisting of daily cumulative precipitation and mean daily air temperature. Secondly, soil surface (0-10cm) properties including texture, bulk density, pH, and total organic carbon. Lastly, pertinent management variables such as crop selection, timing and amount of fertilizer N and manure applications, timing and type of tillage operations. In addition, flooding, weeds, and scheduled irrigation can also be included.

Outputs include annual and daily fluxes of C including CO_2 , CH_4 , DOC, and labile and resistant pools of SOC. Similarly annual and daily fluxes of N, including N_2O, N_2, NO, and NH_3 as well as crop N uptake are output. Daily soil temperatures and calculated water-filled pore space is also recorded.

The CENTURY model (Parton et al. 1993) is a site specific computer simulation model which makes use of simplified relationships of soil-plant-climate interactions to describe the dynamics of carbon and nitrogen in grasslands, crops, forests, and savannas. The model has traditionally been used to estimate CO_2 emissions, but can also be used for N_2O emissions, particularly if a version using a daily, rather than a monthly timestep is released. CENTURY accounts for several agricultural management practices including planting, fertilizer application, tillage, grazing and organic matter addition. Century simulates above and below ground phytomass production as a function of soil temperature, available water, and nutrient availability. It is composed of a soil organic matter/decomposition submodel, a water budget model, a grassland/crop submodel, a forest production submodel, and management and events scheduling functions. It computes the flow of carbon, nitrogen, phosphorus, and sulfur through the model's compartments. The current public release of CENTURY runs on a monthly time step, which is not acceptable for quantifying moisture sensitive emissions of N_2O, but a version with a daily time step has recently been tested (Frolking et al. 1997) and should be released soon. Most simulation models are aimed at either quantifying N_2O or CO_2 emissions, without doing a perfect job for both gases. Mitigation measures for one gas may increase emissions of another radiative greenhouse gas, thus it is desirable to develop a model which provides good estimates for both gases.

Expert-N is not a typical process model, but more of a development system for various nitrogen turnover models to simulate the N cycle in agricultural soils (**Baldioli et al, 1994**). The system has a modular structure and allows for exchange of modular components to compare different algorithms describing the same process. Modular components are available for soil water flow, soil heat, N transport and for crop growth. Additional user defined submodels can also be included to enable the user to analyse the impact of different or new modelling approaches on N_2O emissions, component by component. The modular structure makes it an ideal program for research and for agricultural management where different levels of data are available. The model has a user friendly windows interface, for selecting model components and entering input data. It is primarily developed for European conditions but will soon be adapted for North American conditions. Experimental data, modelling results and expert opinion can be used to develop expert systems and/or metamodels. Metamodels are simplified equations statistically derived from observed or modelling results. The equations may have variables such as precipitation, crop type, soil type, and management and provide a quick and easy method of estimating N_2O emission. Research will soon begin to incorporate a greenhouse gas module into Canada's Regional Agricultural Model (CRAM).

Model validation for Canadian conditions.

Rigorous testing of mathematical models that attempt to characterize many processes is usually carried out during model development. However, due to the scope and complexity of such models, errors can still be present in process development, code syntax, and mathematics. It is not uncommon for such errors to go undetected before the model is used for major scientific, policy, and management scenarios. Smith et al (1998a) tested the performance of the DNDC model (version 5.2) at sites in St. Louis, Saskatchewan and Ottawa, Ontario and found basic errors in soil temperature calculation, soil/root respiration routines, and on the effect anhydrous ammonia addition as fertilizer has on N_2O emissions. Coding errors are common and to be expected but sometimes overlooked in model testing by the scientific community.

Validation of processes within a model is a more difficult task. Some processes can be compared to other models and theoretical equations, but invariably good experimental data sets are required to test a model. Such data sets are limited, and often key processes are not examined. The experimental sites mentioned above provided detailed N_2O emission and soil nitrogen chemistry data for testing the DNDC model under a wide range of soil types, climatic conditions, and agricultural management practices. Smith et al (1998a) found that the data input for the DNDC model was not of sufficient detail to characterize the moisture difference between the landscapes. The DNDC estimates of total yearly emissions of N_2O from the field sites near St. Louis, Saskatchewan were too small by 10% for the footslope landscape and too large by 296% for the shoulder landscape. Also, in some instances, the DNDC model underestimated N_2O emissions during spring thaw and snowmelt. Several other studies have found that N_2O flux is highest in the spring (Goodroad and Keeney, 1984; Parsons et al., 1991; Groffman et al. 1993; Burton and Beauchamp, 1994; Corre et al., 1995). Higher denitrification can occur due to higher moisture contents as a result of snowmelt. Also, more nitrogen may be available due to low plant activity. Furthermore, high N_2O emissions may result from changes in solubility and N_2O that had been accumulated under a frozen soil layer and then later diffuse upon snowmelt and thawing (Goodroad and Keeney, 1984; Burton and Beauchamp, 1994). The model predicted N_2O emissions within 23%, on average , for three manure treatments at the Ottawa site.

The results from IPCC guideline calculations at the Saskatchewan sites showed an under-estimation of 54% for the footslope and an over-estimation of 161% for the shoulder. The results indicate that both the DNDC model and the IPCC protocol were of similar quality for estimating N_2O emissions.

A summary of the testing and comparison of four N_2O emission models at three temperate agricultural sites has recently been published by Frolking et al. (1998).

It is difficult to address the level of uncertainty in modelling. Uncertainty exists in model input, model development, and in our understanding of the processes involved. It would be useful to predict the uncertainty in model estimates by stochastic means. Such an analysis does, however, require variances of input parameters, which may not be available. For instance, when running a

model using national landscape databases the soil characteristics form the Canada Soil Information System (CanSIS), consists of data measured at different scales and estimated data, each data set having different ranges of variance. Some of the data itself is estimated from models. One way to estimate uncertainty is to compare results to what measured values are available.

Estimating N_2O emissions at a provincial or national level

For a country as large as Canada, with all it's diversity in climate, soils and agricultural management, one would expect difficulty in coming up with a good estimate of N_2O emission, especially since N_2O emissions are the most difficult agricultural greenhouse gas emissions to integrate over space and time. Field trials have been known to produce estimates that are almost an order of magnitude different, from one year to the next. Li and Harris (1996) used the DNDC model on a national level to estimate N_2O emission from each state of the United States. Smith et al. (1998b) used the DNDC model to estimate N_2O emissions from agricultural soils in Canada for the years 1990, 1994. Simulations were carried out for various crops on 15% of the agriculturally designated Soil Landscape of Canada polygons. DNDC estimates were compared to estimates from IPCC protocol (Monteverde et al, 1998). The DNDC model estimated that 46.2 and 44.3 kt N_2O-N were emitted in 1990 and 1994, respectively, whereas the IPCC protocol indicated that 39.1 kt N_2O-N were emitted in 1991. Considering all the variability in N_2O emissions it is surprising that the IPCC estimates were within 15% of the estimates from the DNDC model. The results in Table 1 show that estimates of yearly N_2O emission by DNDC and IPCC were close, within all provinces except Quebec and Saskatchewan. As indicated earlier, the DNDC model overpredicts N_2O emissions from the dryer shoulder soils in Saskatchewan.

Direction for future research.

i) Model testing at agricultural sites in Canada is needed. Models such as Expert-N, as well as the daily CENTURY model may eventually produce more accurate estimates than did the DNDC model or IPCC protocol. Further improvements will be required based on this testing. It is very

important that models do a good job in estimating N_2O emissions during spring thaw, a period during which >50% of the emissions for the entire year may occur.

ii) Comparisons of a more rigorous model such as ECOSYS (Grant et al, 1996) with less data intensive models should be made to assess their ability to simulate like processes.

Iii) More experimental data on N_2O emissions from different crops, crops rotations, and management scenarios is needed at sites within Canada, to improve the understanding of processes within models and thus reduce modelling uncertainty.

iv) Model development should be focussed on both CO_2 and N_2O emissions, so that mitigation of greenhouse gases can be analysed with one tool.

v) Development of an expert system for examining mitigation of N_2O emissions from agricultural soils in Canada. Policy Branch of Agriculture and Agri-food Canada is currently expanding CRAM to better assess emissions of N_2O, CO_2, and CH_4 from agriculture. Expert systems need to include components of models plus professional opinion.

vi) Emphasis should be placed on communication between N_2O researchers and the authors of N_2O models. A workshops is currently being organized by R. Desjardin and J. Keng on reducing N_2O emissions from agroecosystems.

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Table 1 Estimated rate of N_2O emission from agricultural soils in Canada

Province	Rate of N_2O-N emission (kg ha $^{-1}$)			Total N_2O-N emission (kt)		
	1990 (DNDC)	1994 (DNDC)	1991 (IPCC)	1990 (DNDC)	1994 (DNDC)	1991 (IPCC)
Atlantic	1.44	1.05	0.82	0.9	0.66	0.52
Quebec	1.15	1	2.22	1.78	1.55	3.44
Ontario	1.25	1.2	1.36	8.1	7.73	8.77
Manitoba	1.01	0.88	0.92	6.45	5.58	5.85
Saskatchewan	0.67	0.69	0.39	13.56	14.11	7.86
Alberta	1.13	1.07	0.9	14.55	13.75	11.51
British Columbia	0.68	0.72	0.91	0.86	0.9	1.15
Canada	0.93	0.9	0.96	46.21	44.28	39.07